UCRL-JC-131510
PREPRINT

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This paper was prepared for submittal to the
25th European Conference on Laser Interaction with Matter
Formia, Italy
May 4-8, 1998

July 20, 1998

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Abstract

The National Ignition Facility (NIF) is a MJ-class glass laser-based facility funded by the Department of Energy which has achieving thermonuclear ignition and moderate gain as one of its main objectives. In the summer of 1998, the project is about 40% complete, and design and construction is on schedule and on cost. The NIF will start firing onto targets in 2001, and will achieve full energy in 2004. The Lawrence Livermore National Laboratory (LLNL), together with the Los Alamos National Laboratory (LANL) have the main responsibility for achieving x-ray driven ignition on the NIF. In the 1990's, a comprehensive series of experiments on Nova at LLNL, followed by recent experiments on the Omega laser at the University of Rochester, demonstrated confidence in understanding the physics of x-ray drive implosions. The same physics at equivalent scales is used in calculations to predict target performance on the NIF, giving credence to calculations of ignition on the NIF. An integrated program of work in preparing the NIF for x-ray driven ignition in about 2007, and the key issues being addressed on the current ICF facilities [(Nova, Omega, Z at Sandia National Laboratory (SNL), and NIKE at the Naval Research Laboratory (NRL)] are described.

***This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.**

1. Introduction

The National Ignition Facility (NIF) shown in Figure 1 is a 192-beam, multi-megajoule glass laser facility which will be sited at Lawrence Livermore National Laboratory (LLNL). The 10 m diameter aluminum target chamber is shown on the lower right with 24 clusters of four beams (quads) of beams entering into the top of the target chamber and 24 clusters of quads from beneath the target chamber. There are two separate laser bays. The laser consists of a 4 pass cavity amplifier section followed by double pass booster amplifier section. At the top left on Figure 1 is the Optics Assembly Building for clean assembly of the modules of the laser. The facility is funded by the Department of Energy and the project to construct the facility has followed the DOE processes for large capital acquisitions. Mission need (CD1) was agreed in January 1993, allowing a comprehensive Conceptual Design Report (National Ignition Facility Conceptual Design Report). Project start (CD2) was in October 1994, with Congressional funding for preliminary or Title I design in January 1996. Start of construction (CD3) was March 1997 and completion of detailed design (Title II) is occurring in 1998. These activities have occurred on a schedule which was written in 1993 and has been adhered to, giving credence to future predictions of schedule.

One of the NIF's principal goals is achieving thermonuclear ignition. A high level of precision is required in laser and target performance and accuracy of calculations to achieve the demanding conditions for ignition. Based on our Nova and Omega experience, we believe that with adequate planning and resources we will achieve ignition with x-ray drive about 2007.

2. The scientific basis of the NIF laser system

One of the main missions of the NIF is achieving thermonuclear ignition and moderate gain, first with x-ray driven implosions of deuterium-tritium (DT) filled capsules, and then with directly-driven implosions. Thermonuclear ignition occurs when the alpha particle deposition in the hot DT core exceeds conduction and radiative energy losses and causes significant heating, in turn increasing the alpha particle deposition. This occurs at thermonuclear output ~ 100 kJ for the type of "hot spot" (Haan *et al.* 1995, Krauser *et al.* 1996, Dittrich 1996) ignition targets considered for the NIF. A near-term goal of the NIF is to achieve multi-megajoule thermonuclear outputs with one of the hot spot target designs presently being considered, which in two-dimensional and partial three-dimensional calculations with beryllium ablator capsules (Dittrich 1996) produce multi-megajoule gain with about 1 MJ absorbed into a hohlraum.

The scientific basis of the critical hohlraum and capsule physics needed for ignition has been reviewed extensively by the DOE mandated Inertial Confinement Fusion Advisory Committee (ICFAC) and 1990 National Academy of Science (NAS) Review (National Academy of Sciences Review of the Department of Energy's Inertial Confinement Fusion Program, Final Report). The reviews have been technically intensive and generally supportive. On the basis of these reviews, the Secretary of Energy agreed to construction start (CD3) in March 1997.

The laser specifications for the NIF have been set by the requirements to achieve x-ray driven ignition for a set of hot spot ignition designs with a >40% margin in the laser power and energy. The principal laser specifications are:

Laser wavelength	0.35 μm
Laser energy and power	1.8 MJ and 500 TW in a temporally-shaped pulse absorbed in the hohlraum

Number of beams	192 in 48 quads, 4 beams/quad
Number of beam cones	4:2 inner cones at 24°-28° , 2 outer cones at 48° to 60°

This beam geometry is the configuration for x-ray drive with cylindrical hohlraums, as shown at the top of Figure 2. To increase the versatility of the facility, provision has also been made to allow the target chamber to field direct drive targets, as well as tetrahedral hohlraums (Phillion & Pollaine 1994) for x-ray drive. As shown in Figure 2, this can be achieved by moving 2 x 4 quads of beams from the inner cones and 2 x 8 quads of beams from the outer cones closer (~72° to the axis) to the equator of the target chamber. The nonuniformity of direct drive in spherical harmonic modes, modes L=1-20, will be approximately 1% for this geometry. Provision has also been made to upgrade the smoothing of the laser beams from one-dimensional smoothing by spectral dispersion (SSD) to two-dimensional SSD. This modification will probably result in a speckle smoothness for high L modes (21-500) of 2–3% averaged over the pulse. This work, and the effect of laser beam smoothing on imprinting with an ultra-smooth KrF laser, is presently being vigorously investigated on the Omega laser at the University of Rochester and the Nike Laser at the Naval Research Laboratory (Bodner, Lehmberg, & Obenschain *et al.* 1998). At this stage of development these and other concepts are still being developed to increase the level of speckle smoothness for direct drive. The main cost of the NIF is in the glass power amplifiers and so modifications to the final optics or the oscillators to incorporate improvements, such as 2D-SSD or novel phase plates, can be incorporated at relatively low cost.

The other principal objective of the NIF is for the Nuclear Weapons Stockpile Stewardship Program (The Stockpile Stewardship Plan: Second Annual Update (FY 1999)). The facility also has other objectives, for nuclear weapons effects testing, scientific outreach and economic competitiveness, and it is designed to have a high degree of flexibility, e.g., energies in excess of 2 MJ at 0.35 μm will be possible for pulses longer than the 3.5 nsec shaped ignition pulse. This will allow radiation temperatures in excess of 100 eV and ablation pressures in excess of many megabars for 10 nsec in macroscopic-sized hohlraums (64 mm long x 40 mm diameter); target irradiation at a wavelength of 0.53 μm will be possible; target irradiation up to 25 cm from the chamber center will be possible.

At the present time (summer 1998) the project is nearly half way to completion in terms of elapsed time (conceptual design started in 1993, project completion is 2003) and funds expended (about 41% of funds will have been spent or committed by September 1998), and the project is on cost and on schedule.

Although the NIF is a 192-beam laser, the basic eight-beam laser module (or bundle) is a 4 beam high by 2 beam wide amplifier module. A major feature of lasers is their modularity and the system will be activated module by module. The first bundle of 8 beams will be operational in summer 2001. The early use of the first bundle will give operational experience and will allow experiments with energy up to 80 kJ at a wavelength of 0.35 μm for ignition studies starting in the summer of 2001. Subsequently, other beam bundles will be activated allowing increasing levels of laser beam energy for experiments. Project completion (CD4) will be at the end of 2003, with half of the beams activated. Full energy will be available on target at the end of 2004. X-ray driven ignition should be achieved a few years later.

One of the NIF's missions is scientific outreach. In a preliminary form this is being tested on Nova with the Scientific Use of Nova (SUN) program. In addition, DOE funds the National Laser User Facility at the University of Rochester and the DOE University Grants Program. At LLNL, ten percent of

Nova's shots have been devoted to SUN since 1996. From 67 proposals from universities over the three years of SUN's operation, 22 have been approved resulting in over 20 publications and 20 invited talks at scientific conferences in areas such as laboratory astrophysics, equation of state, material strength, etc.

3. The Nova technical contract and related work and confidence in ignition

The key scientific hohlraum issues of laser hohlraum coupling and x-ray drive symmetry were specified by the NAS in 1990 (National Academy of Sciences Review of the Department of Energy's Inertial Confinement Fusion Program, Final Report) in seven performance goals [called HLP (Hohlraum Laser Plasma) 1-7]. The key scientific issues relevant to implosions, the hydrodynamic instability issues, and the high convergences required were also specified in another five performance goals [called HEP (Hydrodynamically Equivalent Physics) 1-5]. Concurrence that these goals known as the Nova Technical Contract (NTC) had been achieved was given by the ICFAC in November 1995 and documented (LLNL ICF Quarterly Report, July-September 1995).

The target designs for ignition and moderate gain with x-ray drive require about 1 MJ of energy absorbed in a hohlraum target, producing a peak radiation temperature T_r of 250-300 eV. For HLP1 and 2, Nova experiments showed values of T_r of >270 eV for 1 ns square pulses, and over 210 eV for shaped pulses in lined hohlraum, respectively (LLNL ICF Quarterly Report, July-September 1995). Further experiments in gas-filled hohlraum's attained 230 eV for shaped pulses (Glenzer *et al.* 1998). For ignition, drive temperatures higher than 250-300 eV would allow lower laser energies but are more difficult to achieve because the higher intensities in the laser beam may enhance laser plasma instabilities, resulting in increased scattering of the laser beams and a reduction in laser hohlraum coupling or drive symmetry. Nova experiments with laser intensity up to 2 x 10^{15} W/cm^2 at the electron densities ~10^{21} cm^{-3} and scale lengths 1-2 mm of NIF ignition hohlraums (@ 0.35 μm wavelength) showed <10% loss of laser energy into SBS and SRS, satisfying HLP5. Much lower drive temperatures with higher aspect ratio capsules are similarly precluded because of hydrodynamic instabilities. Planar Nova experiments with hydrodynamic instability growth factors (Kilkenny *et al.* 1994) up to 70 showed a quantitative understanding of the ablative stabilization of the Rayleigh-Taylor instability under ignition relevant x-ray drive conditions, satisfying HEP2.

For ignition, precise symmetry control is required with a time averaged drive asymmetry (pole/equator) not exceeding 2%, because of the need to achieve a high radial shell convergence C_r (initial capsule radius/final fuel radius) in the range 30-40. On Nova, the variation with time of drive symmetry is ~ ±15% because there are only single "rings" of beams. Furthermore, this "ring" of beams has significant azimuthal dependence because it is made up of only 5 beams. Consequently, an upper limit to C_r of ~ 10 is possible on Nova for targets with NIF-like hohlraum to capsule size ratios. However, we have been able to exceed this limit in a series of experiments (HEP1), where we decreased the size of the capsule relative to the hohlraum in order to increase the level of drive symmetry (Cable *et al.* 1994). In our C_r = 10 experiments, we have also demonstrated control of time-integrated drive symmetry to ~ 1% by adjusting the laser pointing into the hohlraum (HLP4) (Landen *et al.* 1996). On NIF, the high level of time-dependent symmetry control requires two rings of beams with slightly different pulse shapes, as well as a gas-filled hohlraum to reduce the motion of the x-ray emitting region. Omega with 60 beams can go half way in a geometric sense, to demonstrating NIF performance.

Initial experiments with gas-filled hohlraums on Nova with unsmoothed beams demonstrated an unexpected shift in the experimental tuning of best symmetry compared to calculations and empty hohlraums. This was hypothesized as being due to laser beam filamentation in ~10% flowing critical density plasma. Subsequently, laser beam smoothing was shown to nearly eliminate this shift, producing experimental results matching simulations (Murphy *et al.* 1998).

A wide range of designs is calculated to ignite in 2D and 3D fully integrated calculations with realistic initial target surface finishes for ablators of Be, plastic, and polyimide. For all single shell target designs discovered so far the deuterium-tritium (D-T) fuel must start at cryogenic temperatures and densities, with a surface finish on the interior ice surface of about 1 μm. This level of internal cryogenic surface finishes of D-T layers in mm scale shells has been demonstrated by the natural beta decay process enhancing ablation from thicker regions of ice (Hoffer & Foreman 1988).

The design requirements for direct drive on the NIF have some overlap with x-ray drive, but have some significantly different features, notably the higher degree of smoothing of the laser beams required to avoid imprinting unacceptable hydrodynamic perturbations on the target (Verdon 1993). The program of work for direct drive ignition preparedness is being executed on the Omega laser at the University of Rochester and the Nike laser at the Naval Research Laboratory.

4. Ignition preparedness planning

For x-ray driven ignition, a work breakdown structure (WBS) to prepare for ignition has been agreed between the participants (LLNL, LANL, and SNL) in the US ICF program. The WBS is aligned with the issues listed above, that is hohlraum energetics, drive symmetry and capsule physics. DOE guidelines are that ~42% of NIF's shots will be used for ignition. Scoping of the issues which require experimental resolution and the facilities (Nova, Omega, Z, and NIF), and resources available have produced an approximate schedule for ignition on the NIF, shown in Figure 3. Shown at the top of the figure is the NIF energy available to use for experiments vs. year as increasing numbers of 4 x 2 bundles of NIF beams become available. Before the NIF becomes available, experiments on Nova, Omega, and Z will be used to refine the NIF target diagnostics, laser specifications and target specifications for ignition targets. When Nova closes in summer of 1999, the support program preparing for x-ray driven ignition will shift to the Omega laser at the University of Rochester, Z at SNL, and Nike at Naval Research Laboratory before ignition preparedness experiments start on the NIF in 2001.

For hohlraum energetics, the accuracy of the measurement of x-ray drive will be improved by experiments on Omega. The issues are the closure of diagnostic holes in the hohlraum wall or the use of laser entrance holes for diagnosis. The hohlraum temperature is currently measured to an accuracy of ±5 eV, but with undesirable lower accuracy at the end of the laser pulse. In parallel, the Z machine will be used to develop and "ruggedize" calibrated soft x-ray spectrometers for the NIF.

The main issue for hohlraum energetics, apart from diagnosis, is the level of laser energy backscattered and sidescattered by the turbulent low density plasma in the hohlraum. The plasma turbulence can be stimulated (i.e., stimulated Brillouin and Raman scattering or SBS and SRS) by phase matching conditions with plasma waves at a sufficiently high laser beam intensity. However, laser beam smoothing reduces the levels of backscattered energy by reducing the fraction of laser beam at high intensity. The Nova Technical Contract (NTC) experiments showed that beam smoothing reduces the levels of SBS and SRS in gas-filled hohlraums. As shown in Figure 3, Nova will be used to test the exact beam smoothing by spectral dispersion (SSD) characteristics envisioned for the NIF (~ 17 GHz). After the closure of Nova in the summer of 1999, the Omega laser will be used to measure the thresholds for laser plasma interactions at a function of laser intensity and smoothing scheme (Figure 3).

The Omega laser will be used to demonstrate symmetry control of the higher order Legendre modes (P_4, P_6, P_8) to show that a high convergence implosion (C_r ~ 20) with NIF-like hohlraum case/capsule ratio can be achieved (Figure 3). Diagnostic development activities in this area will also be conducted on Omega, particularly the development of symmetry measurement techniques, at NIF-scale for the T_{rad} ~ 80 eV of the NIF drive pulse.

Figure 3 outlines the plan for developing our understanding of capsule physics. Nova will be used to develop techniques to more accurately measure the shock timing for the NIF. Active shock breakout techniques coupled with more accurate measurement of the equation of state (e.o.s.) of cryogenic deuterium ice will be required, particularly for the foot of the laser pulse (DaSilva, L. et al. 1997). The Z facility at SNL will also be used for some of these experiments.

Once the NIF starts to become available in 2001, the laser control and measurement techniques must be refined to meet the requirements of drive symmetry and shock timing. Further experiments before the NIF will improve our detailed and quantitative knowledge of the material data—x-ray opacity and material equation of state needed. Nevertheless, NIF hohlraum symmetry and pulse shape fine-tuning will be required on the NIF system for ignition.

Although there is a lot of uncertainty in predictions of schedules nearly ten years in the future, a plan is essential and in this plan ignition experiments are anticipated ~2007. As shown in Figure 3, once x-ray driven ignition is achieved, the laser beam geometry can be reconfigured (Figure 2) to a direct drive configuration.

Remaining physics issues before the NIF

(a) **Hohlraum energetics:** Nova experiments in the early nineties (Kauffman *et al.* 1994) demonstrated an accurate understanding of empty hohlraum energetics given the hohlraum absorption. However, the NIF hohlraums are filled with plasma with a considerable beam path traversing plasma at ~ 10% critical density with the laser beam intensities in the range of 0.5-2 10^{15} W/cm^2 when laser plasma instabilities can cause significant laser light backscatter by stimulated processes (SBS or SRS). Linear theory gives high gain coefficients but does not address the absolute levels of backscatter in the non-linear regime. To simulate the conditions for laser plasma interactions on the NIF, hohlraums on Nova have been filled to one atmosphere of methane. NIF-like beam smoothing on Nova with plasma conditions (methane-filled hohlraums and gas bags) similar to the NIF (MacGowan *et al.* 1998, Glenzer *et al.* 1998) in terms of laser beam intensity and linear gain coefficients for SRS and SBS (Figure 4) shows that phase plates and smoothing by spectral dispersion (SSD) reduce backscatter losses from 15% to a few percent. Because of the increased absorption, the radiation temperatures increase from 200±5 eV to 213±5 eV. For shorter pulse lengths in shaped pulses peak temperatures up to 230 eV are measured with a standard deviation of ± 4 eV in gas-filled hohlraums, in agreement with LASNEX calculations. The scaling of the radiative temperatures in the gas-filled hohlraums is also in agreement with a simple Marshak scaling with x-ray conversion coefficient ~ 0.9.

Nova experiments so far have used low frequency (few GHz) modulators for the SSD. On NIF it is planned to use 17 GHz modulators for SSD and this, together with polarization rotation (Lefevbre *et al.* 1998), is being tested on Nova before its shutdown. Recent experiments are very promising and show that polarization smoothing drastically reduces SBS. If these results stand scrutiny, there will be a strong incentive to install polarization smoothing on NIF.

The predictive capability for laser plasma interaction developed by the community is presently much less quantitative than the radiation hydrodynamic capability in codes such as LASNEX, however it will be incrementally improved before NIF operations begin. Recently, a comparison of plasma physics theory with experiments has been possible with the use of a 3–D wave-tracing code F3D (Hinkel *et al.* 1998) to quantitatively predict the onset of filamentation. This code is being modified to simulate backscattering using wave envelope methods. The goal is a quasi-predictive capability for onset of high levels of backscatter for higher intensity hohlraums with SSD and polarization smoothing on NIF.

(b) Hohlraum symmetry: The x-ray drive ignition pulses typically have radiative temperature 'foots' at $T_{rad} \sim 100$ eV, lasting for ~7 nsec before ramping up to a 3-4 nsec peak with $T_{rad} \sim 300$ eV. Drive symmetry is most simply represented by the Legendre harmonics P_0, P_2, P_4, etc., where only the low orders matter because of the large hohlraum smoothing effect for high order modes. For a 30-40 fold convergence ignition implosion, the time integrated symmetry must be less than 2% in P_2 with time varying swings less than 10% for 3 nsec in the foot and less than 5-10% during the peak (Haan *et al.* 1995). Earlier work developed the technique of imaging the shape of the x-ray emission of an implosion, and imaging in hard x-rays the motion of the x-ray emitting area to measure drive asymmetry (Suter *et al.* 1994). Another technique to measure the time dependence of the drive asymmetry is from x-ray backlit images of the ablation front in a low density witness ball placed at the center of a hohlraum (Amendt *et al.* 1997). LASNEX and simple analytic scaling shows that a 10% modulation in the drive (P_2/P_0) produces a 2-3 μm modulation in the observable a_2 (second Legendre coefficient in radius). On Nova, measurements of a_2 have been made with error bars as small as 1 μm (Amendt *et al.* 1997). In addition to the second Legendre coefficients the fourth, sixth, and possible eighth coefficients need to be measured and controlled to achieve ignition on the NIF. Experience gained at Nova and Omega in 1998-2001 will allow a more accurate assessment of the measurement accuracy of drive symmetry for higher order modes and control on the NIF. To be able to pick out higher modes, the low order modes must be reduced.

The Omega laser allows up to 40 beams to enter a cylindrical hohlraum (Decker *et al.* 1998). Rudimentary pulse shaping control has been performed on the Omega laser by delaying the inner cones of laser beams with respect to the outer areas. In addition, significant diagnostic issues need to be addressed. New techniques for improving the quantum efficiency of gated micro-channel plate detectors (Kilkenny 1991) need to be implemented. Imaging techniques that can be used in the relatively hostile environment of the NIF target chamber must also be developed.

On Nova the level of asymmetry caused by intrinsic or random variation is greater than on NIF, principally because of the lower number of beams. Three dimensional radiation hydrodynamic simulations and experiments (Marinak 1996) show that for smooth capsules the neutron yield of high growth factors implosion on Nova should be the measured 30% of the calculated 1D yield for C_r ~12. The Omega laser has the capability of using 40 of its 60 beams into a hohlraum producing better symmetry than Nova (Decker *et al.* 1998). On Omega, the calculated yields of higher convergence (C_r up to 20), can be ~60% of clean 1D. Recent Omega hohlraum experiments exercising a NIF-like multiple beam core geometry have been encouraging in producing yields close to this fraction of 1D yields on some shots.

(c) Capsule physics: In calculations, target performance depends critically on shock timing. For example, a 0.5 nsec shift to earlier time in one of the shocks of the x-ray drive (Figure 5-left) produces a pressure in the fuel that is too high (upper curve in Figure 5-right) with a lower final pressure (Figure 5-central) producing a neutron yield of 0.2 MJ compared to a "well-timed" implosion with 10-15 MJ.

Simulations show that the shock timing of the four shocks of a NIF capsule must be measured and timed to an accuracy ~ 0.1 nsec (significantly less than the 0.5 ns of Figure 5) with respect to each other as they break out of the inner surface of the cryogenic deuterium-tritium. Techniques to make accurate measurements of the equation of state (e.o.s.) by radiographically measuring the piston velocity U_p, as well as the shock velocity U_s, have been refined sufficiently accurately to make U_s and U_p measurements of cryogenic deuterium and plastic to an accuracy in density $\pm$12-15%, sufficient to experimentally distinguish between various theories (DaSilva *et al.* 1997) for shock timing tuning. In the early years on the NIF, techniques developed on Nova and Omega for measuring cryogenic e.o.s.—active shock breakout, Velocity Interferometry System for Any Reflector (VISAR), and high resolution radiography will be used to measure U_s and U_p. Nova experiments have made e.o.s. measurements on the Hugoniot. Off Hugoniot measurements will be made on Nova in 1999. Final measurements will be made on NIF (Figure 3) to accurately determine the laser pulse shape before ignition implosions are attempted.

The choice of ablator material for the first x-ray driven ignition experiments needs to be made about ~2000 because the details of the cryogenic manipulator depends on the choice of the material. We anticipate, based on experience with the cryogenic manipulator at the Omega laser, that it will take 5 years to develop, design, fabricate and test the NIF cryogenic manipulator although there is an expectation that the cryogenic manipulator on NIF will benefit from the Omega experience.

Table I represents our present assessment of the issues determining the best ablator for the NIF out of beryllium, polyimide, and brominated plastic.

	Be	polyimide	CH
ignition margin (at a given σ_{DT})	A	B	C
fabrication maturity	C	C	B
shell characterization (uni formp and dopant concentration?)	D	B	B
DT fill?	D	A	A
measure $\sigma_{DT\,ice}$?	E	A	A
auxiliary DT smoothing?	E	A	A
shell strength (important for transport)	B	C	D

Prospects

- **A** **Excellent**
- **B** **Very Good**
- **C** **Good**
- **D** **Debatable**

Table I represents our present assessment of the issues determining the best ablator for the NIF

For a given surface finish there is no question that Be is the best ablator material because more mass is ablated since it has the lowest x-ray opacity. However, although brominated plastic, the material with which we have the most experience on Nova is not the best ablator, its fabrication maturity is greatest and the target can be made today. The specification in sphericity of the underlying plastic materials can nearly be achieved. Plastic and polyimide shells are easily filled with deuterium-tritium by diffusion, in contrast to Be which is nearly impermeable except at high temperatures. Machined Be hemi-shells, being pursued by LANL, might be bonded under high pressure fill gas or filled under pressure with small enough perturbation that the fill hole does not perturb the implosion. It is not possible to measure the deuterium-tritium fill of Be capsules or characterize a frozen fuel layer by optical means since Be is not transparent. It is also hard to augment the layer smoothness by infrared on microwave heating because of the high opacity of Be to optical and radio frequency radiation. Both Be and polyimide have the advantage that their material strength could allow transport of pressurized (350 atmosphere) capsules at non-cryogenic temperatures. A more quantitative assessment of these issues, as well as some possible innovative solutions, are being investigated between now and 2000 by LLNL, LANL, and General Atomics (GA).

5. NIF ignition diagnostics

The Nova and NIF diagnostics have much in common (Kilkenny 1992, Kilkenny 1995, Leeper 1998), and much of the development work is presently complete. The specifications and placement of the first score of the diagnostics has been agreed to by a Joint Central Diagnostic Team. The time when they will be required is determined by the program of work, however, for the ignition campaign, Figure 6 shows that the diagnostics for ignition are needed in a phased way as the complexity of the experiments to be executed increases.

To measure and adjust the synchronization of the laser beams, two x-ray streak cameras will resolve and synchronize the x-ray emission from up to 48 laser spots focused at one time onto a target. The x-ray streak cameras will be housed in manipulators (DIMs) with common interfaces with Omega and Nova manipulators, which will allow their use from different viewpoints.

The pointing and focusing of clusters of beams will be confirmed by imaging the position of x-ray spots with respect to fiducial positions with gated x-ray imagers. The gated x-ray imagers will use x-ray pinhole imaging to resolve the x-ray emitting spots.

The hohlraum radiation temperature will be measured by two techniques that have been successfully used on Nova. The x-ray flux escaping from a small hole in the hohlraum wall, or the laser entrance hole (Leeper *et al.* 1997), will be measured by an absolutely calibrated, broadband, time-resolving x-ray spectrometer. This instrument will either be similar to the Nova Dante system, or will use a transmission grating dispersing the spectrum onto an array of photoconductive detectors.

The radiation temperature will also be measured by the strength and speed of a shock produced in witness plates attached across a hole in the hohlraum wall. This measurement will be made by an $f/10$ ultraviolet telescope similar to the Nova Streaked Optical Pyrometer (SOP) system, with the addition of an active probing system.

Hard x-ray generation in the hohlraum will be measured by an absolutely calibrated, hard x-ray detector system.

The time-resolved drive symmetry will be measured by various surrogate witness balls and shells. The time integrated drive symmetry will be measured by the shape of the x-ray and neutron emission from imploded, full thickness capsules with x-ray emitting dopants added to gaseous deuterium fuel. The shape of the backlit witness balls and x–ray emitting cores will be measured by the time-resolved gated x-ray imagers.

The total neutron emission is an indicator of the symmetry of these implosions and will be measured by total neutron yield detectors. The fuel temperature will be determined from the Doppler broadening of the thermonuclear neutrons measured with the neutron time-of-flight detectors. The shape of the neutron emitting core, an additional indicator of the drive symmetry, will be measured by a neutron imaging system.

Diagnostic ports on the target chamber have been positioned to provide the best possible experiment results, while maintaining an unobstructed view of the target for each diagnostic. The majority of the diagnostic ports will be a 46 cm diameter clear aperture so that experiments using the universal manipulators (DIMs), as well as most others, can be located conveniently for best results. There are only two ICF requirements identified so far for ports larger than 46 cm diameter. These are for the neutron-flight-path and shock-breakout experiments.

Additional diagnostic ports will be added to the target chamber layout before construction to allow for further diagnostics and diagnostics required for nonignition activities such as weapons physics, weapons effects and inertial fusion energy. Because of the expense of using photographic film and its inherent inaccuracy, all image readouts will be electronic.

6. Summary:

A major effort on Nova, and recently Omega, has demonstrated an accurate understanding of the physics of x-ray drive implosions. Although the specifications on targets and lasers are stressing, all of the issues have been addressed. This has been a major contributing factor in obtaining the funding for the NIF. A disciplined, project-oriented approach has ensured the cost and schedule of the NIF has not changed. Operations of the NIF will start in about 3 years. A detailed plan is evolving for the program work needed to attain ignition as soon as possible.

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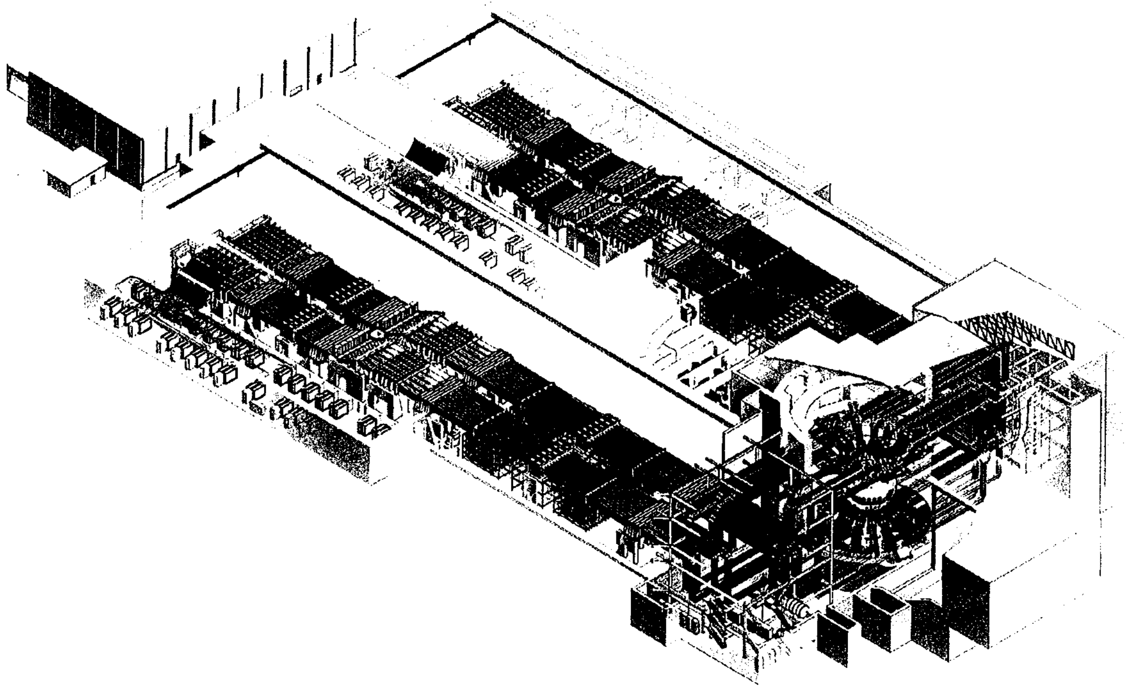

Figure 1. Isometric view of the National Ignition Facility.

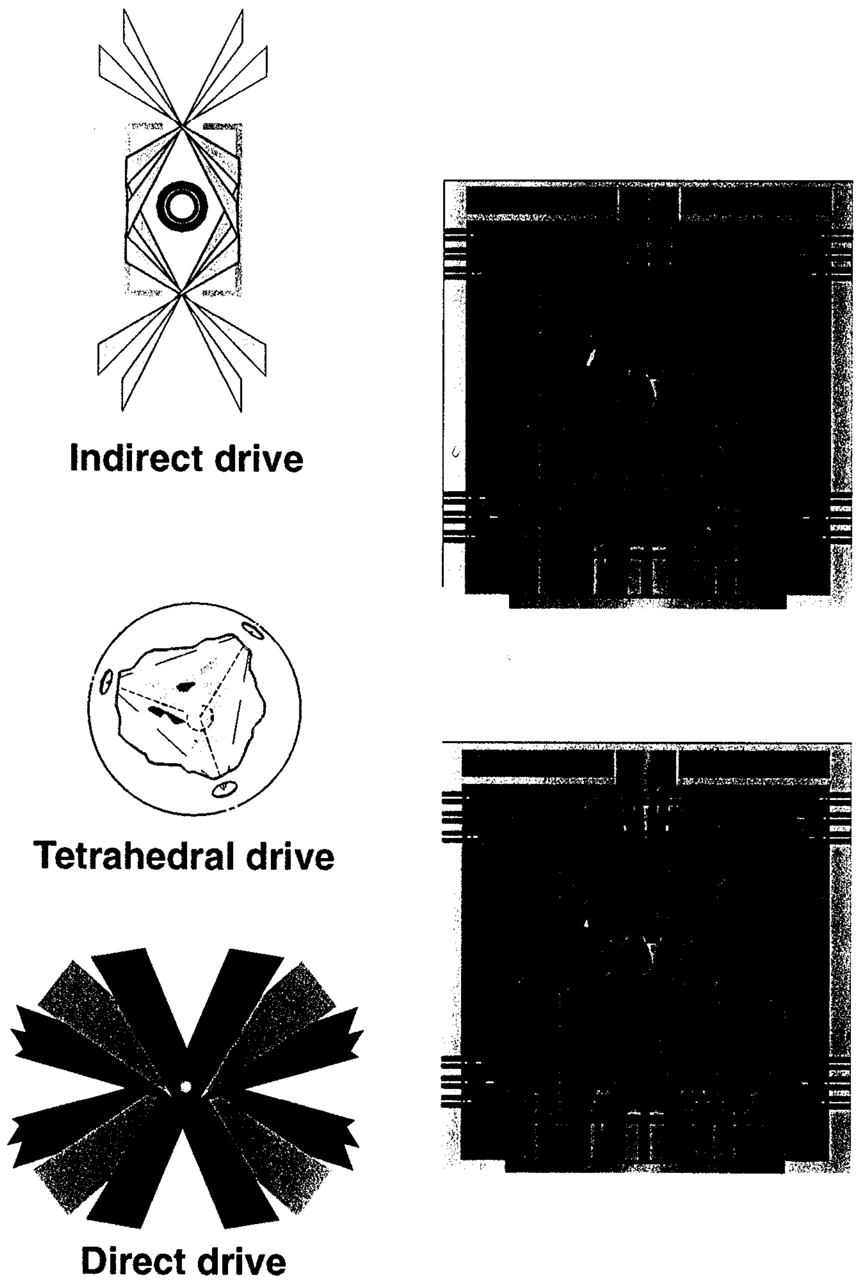

Figure 2. The flexible drive symmetry of the NIF allows cylindrical x-ray drive (upper), direct drive (lower), and tetrahedral x-ray drive (middle).

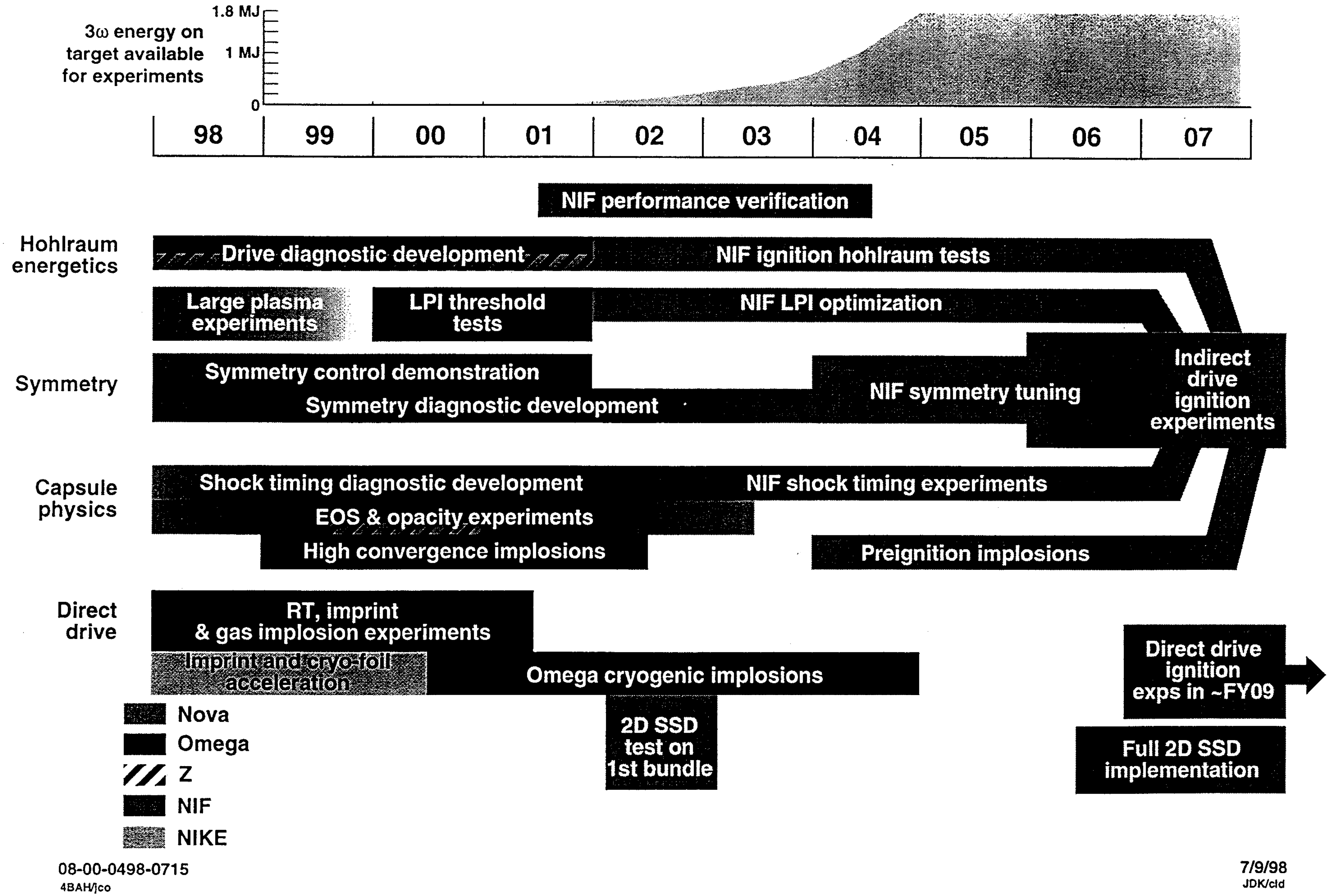

Figure 3. The schedule for ignition preparedness on the NIF using the various facilities of the U.S. ICF Program.

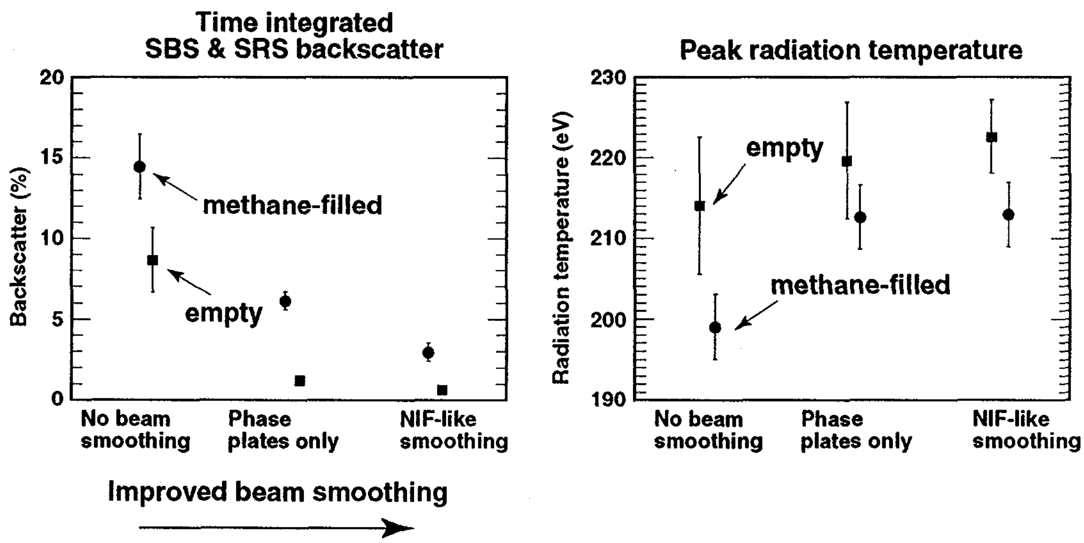

Figure 4. NIF-like beam smoothing on Nova reduces the backscattered laser energy to insignificant levels and increases the radiation temperature.

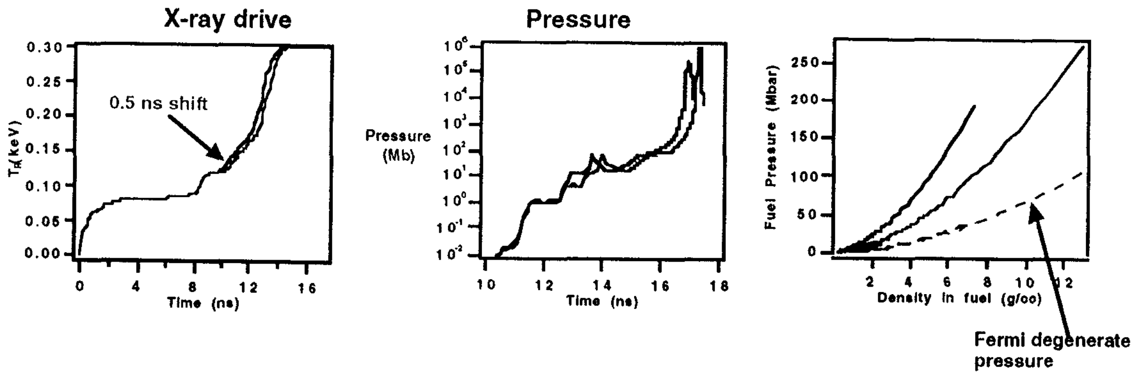

Figure 5. Effect of mis-timing the x-ray drive (left) in increasing fuel density well above an adiabat (right) with a resulting drop in final pressure.

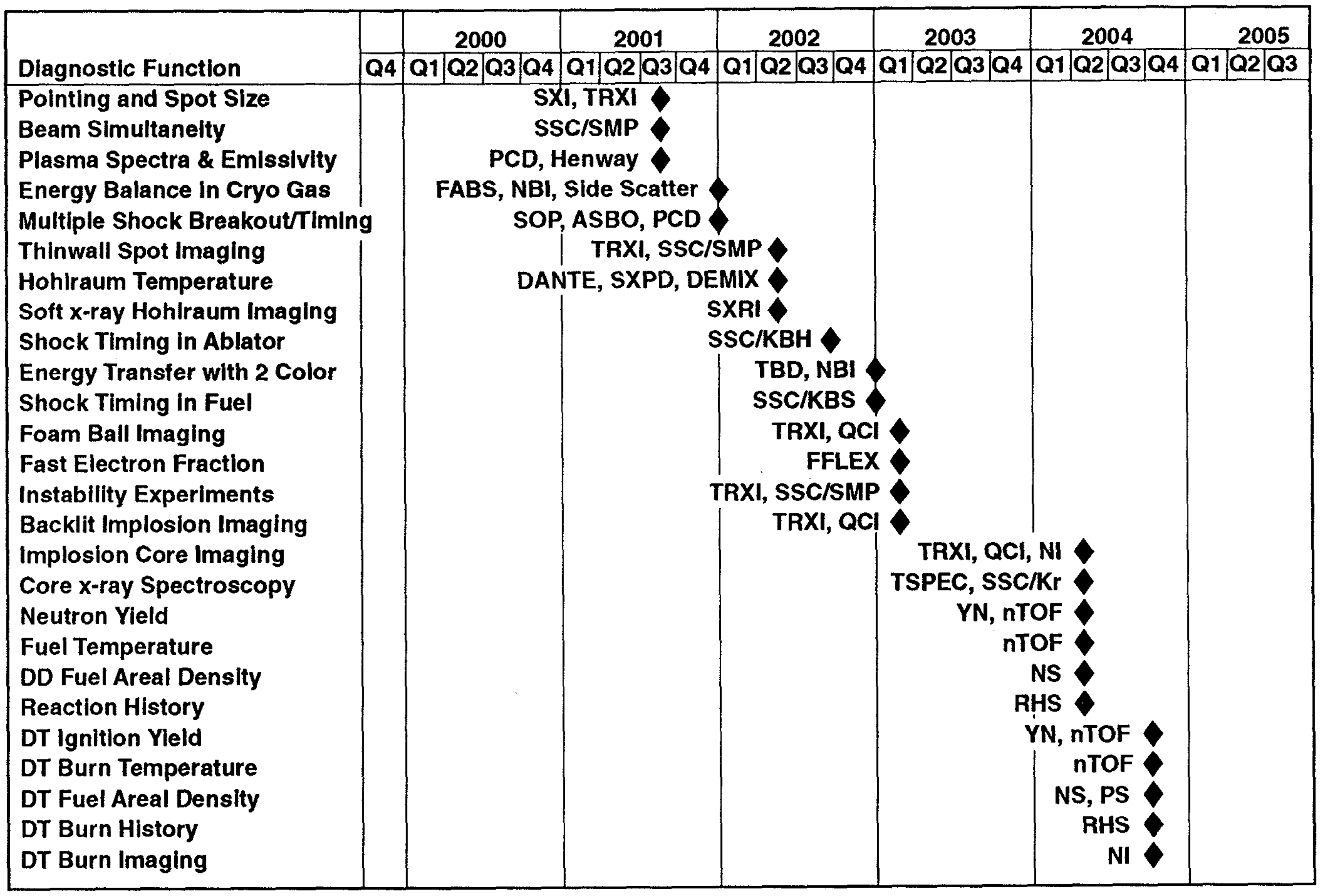

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Figure 6. The schedule of diagnostic implementation required for the NIF ignition plan.